Architecture and petroleum systems of the Alpine orogen and associated basins

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ABSTRACT

The Alpine orogen extends from Gibraltar to the Black Sea and consists of an interlinking system of fold-and-thrust belts and associated foreland and back-arc basins. Although these all evolved in response to convergence of the Africa-Arabian and European cratons, and coeval closure of the Tethys oceanic basins, they differ widely in their architecture and evolutionary history in which such aspects as orthogonal or oblique collision, the intensity of collisional coupling of the evolving orogen with its foreland, and the alternation of compression, transpression and transtension, or even extension, played a significant role.

Recently recorded deep seismic profiles image the crustal architecture of some segments of the Alpine orogen. Progressive, gentle orogenward downflexing of the foreland crust, accommodating foredeep basins, as well as localized crustal roots are evident beneath the axial parts of the Pyrenees and the Alps. However, in the northern and eastern Carpathians, in Languedoc-Provence or in the Betic Cordillera, the Moho remains horizontal or even shallows toward the internal zones of these orogens. This is thought to be related to syn-orogenic back-arc extension, as seen in the Pannonian basin and the Tyrrhenian Sea, or to the opening of the oceanic Algero-Provençal Basin. Seismic tomography images deep lithospheric roots in different segments of the Alpine orogen. Lithospheric slabs appear to be still attached to the underthrusted Apulian-Ionian, East-Mediterranean and Moesian crusts beneath the southern Apennines-Calabrian and Aegean arcs and along the southeastern salient of the Carpathians, respectively.

Effective source rocks are widely distributed within the Alpine orogen and in associated basins. They are alternatively localized in pre-rift, syn-rift or passive margin sequences, the age of which is highly variable. In addition, syn-orogenic foreland basin sequences can host important source-rocks and are frequently the locus of biogenic gas generation. Examples of syn-orogenic oil source rocks are the Oligocene Menilite shales of the Carpathian domain. The Po Plain and the Adriatic foreland basin contain major biogenic gas reserves.

Contrasted thermal regimes and successive episodes of sedimentary and tectonic burial account for the great diversity of petroleum systems identified in the Alpine orogen and associated basins. Each hydrocarbon province is characterized by a very distinct scenario for the timing of source-

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rock maturation and petroleum expulsion, for hydrocarbon migration from effective kitchens to potential trapping domains, and for the preservation of hydrocarbon accumulations.

INTRODUCTION

The Alpine orogen of the Mediterranean area consists of a system of interlinking fold-and-thrust belts and associated foreland and back-arc basins. These differ in the age of their development and deformation, their tectonic setting and architecture. The evolution of all these features is intimately linked with the Mesozoic break up of Permo-Triassic Pangea, culminating in the step-wise opening of oceanic basins forming the Western Tethys, and their closure during the Alpine orogenic cycle.

For a long time, geologists have identified within the Alpine allochthons remnants of the Tethyan passive margins as well as ophiolites, interpreted as remnants of coeval oceanic basins. On the basis of these interpretations the former plate boundaries between Europe, Apulia and Africa were defined (Biju-Duval et al., 1977; Bernoulli and Lemoine, 1980; Dercourt et al., 1986; Favre and Stampfli, 1992). Oceanographic surveys and off-shore drilling have shed light on the origin of the various Mediterranean sub-basins. These are variably floored by remnants of the former Tethys Ocean (Ionian and Libyan seas), newly formed oceanic crusts (Algero-Provençal basin and Tyrrhenian Sea), extended continental lithosphere (Valencia trough, Aegean Sea) and thick continental lithosphere (Adriatic Sea).

Available geological and geophysical data sets, including recently recorded deep seismic profiles, provide a 3D-image of the present crustal architecture of the Alpine orogen. These data permit palinspastic restoration of former oceanic and continental domains and, by applying plate tectonic concepts, a simulation of the plate kinematics which underlay the evolution of the Alpine orogen. Construction of regional palaeogeographic-palaeotectonic maps has considerably advanced our understanding of the evolution of the Alpine orogen and of the sedimentary basins which are associated with it. Yet, remaining uncertainties, for instance about the configuration of the Tethys embayment at the end of the Variscan orogeny (how far to the East had collisional coupling between Africa-Arabia and Europe progressed and was the northeastern margin of Africa-Arabia indeed fringed by an orogen), the timing of opening and closure of the various Mesozoic oceanic basins forming the Western Tethys and the derivation and dimension of some of the tectono-stratigraphic units which are involved in the Alpine orogen, account for major differences between reconstructions proposed by, for instance, Ziegler (1988, 1994a), Stampfli et al. (1991), Dercourt et al. (1993) and Yilmaz et al. (this volume). It is the objective of the on-going Peri-Tethys program to resolve some of these outstanding questions.

As an introduction to this volume, in which selected case history studies on basins and fold-and-thrust belts and petroleum provinces are discussed, this paper aims at providing an overview of the crustal architecture and evolution of the entire Alpine orogen and its associated basins. The role played by Tethyan syn- and post-rift and Alpine syn-orogenic series in the development of petroleum systems will be discussed with reference to the regional examples documented in the following chapters.

ALPINE OROGENS AND ASSOCIATED BASINS

The complex, arcuate geometry of the Alpine orogen was preconditioned by the rift-induced configuration of its forelands, the pattern of oceanic basins and intervening microcontinental blocks and the kinematics of their interaction during the Alpine convergence of Africa-Arabia and Eurasia. The major elements of the Alpine orogen evolved by closure of oceanic basins of variable size and age; such sutures are characterized by internal ophiolitic zones and major nappes. However, a number of fold belts developed by inversion of intra-continental rift zones (e.g. Atlas, Celtiberian range, Provence-Languedoc, Dauphiné, Dobrogea, Crimea). A transitional feature between these two end members are the Pyrenees which evolved out of an inter-continental transform rift zone, characterized by localized mantle denudation.

Remnants of Mesozoic Tethys Versus Neogene Oceanic Crust

According to geophysical data and palinspastic reconstructions, remnants of the Mesozoic Tethys Ocean are still preserved in the Ionian Sea and probably also in the northern parts of the Eastern Mediterranean. Both domains are at present still being subducted beneath the Calabrian and the Cretan and Cyprus arcs, respectively (Fig. 1). Thick Mesozoic and Cenozoic sediments prohibit direct sampling and dating of the oceanic crust in these areas, which could be as old as Permian (first deep marine sediments on the Pelagian block and pelagic series of the Hawasina nappes in Oman; Stampfli et al., 1991; Stampfli, 1996), or as young as Cretaceous (i.e. coeval with the onset of the rotation of Apulia with respect to Africa and rifting of the Syrte Basin in Libya). In the Eastern Mediterranean, the area occupied by oceanic crust is uncertain (Makris et al., 1983; Sage and Letouzey, 1990) and its age is still debated; similar to most of the ophiolitic units accreted in the Alpine orogen, the oceanic part of the East-Mediterranean basin is probably of mainly Triassic to Jurassic age. However, lack of hard information on the nature and age of the East-Mediterranean crust provides for major uncertainties and differences in palaeo-reconstructions retracing the opening of the Western Tethys and its closure during the Alpine orogenic cycle (Ziegler, 1988; Stampfli, 1996; Dercourt et al., 1993; Yilmaz et al, this volume).

In contrast, the oceanic crust of the Western Mediterranean is Neogene in age. Opening of the oceanic Algero-Provençal Basin is dated as Burdigalian by the transition from syn-rift to thermal post-rift subsidence of its margins and by palaeomagnetic data (Vially and Trémolières, this volume). Oligocene-earliest Miocene rifting in the domain of the Gulf of Lyons and the Valencia Trough, culminating in opening of the Provençal Basin, was contemporaneous with northwest-dipping subduction of the Alboran-Ligurian-Piemont Ocean and thus initiated in a back-arc setting (Maillard and Mauffret, 1993). However, sea-floor spreading in the Algero-Provençal Basin cannot be related to back-arc extension (Ziegler, 1994b). On the other hand, Late Miocene and younger rifting in eastern Sardinia and in Tuscany (Keller et al., 1994; Spadini et al., 1995), as well as magnetic anomalies and results of deep-sea drilling, date opening of limited oceanic domains in the Tyrrhenian Sea as Pliocene and Quaternary (Wezel, 1985). This young oceanic basin developed in a back-arc setting with respects to the Apennine orogen; rifting and opening of the Tyrrhenian Basin behind and above the west-dipping Apennine subduction zone was contemporaneous with continued subduction of the Apulian-Ionian crust (Serri et al., 1993).

Back-arc extension, even if it did not always culminate in opening of oceanic basins, as e.g. in the Aegean Sea (Jolivet et al., 1994) and the Pannonian Basins (Royden and Horváth, 1988; Tari et al., 1992), causes rapid subsidence of formerly elevated compressional structures (negative inversion). Under such conditions, pre-existing compressional detachment faults can be tensionally reactivated, as seen in the Oligocene-early Miocene evolution of the the Languedoc coast (Vially and Trémolières, this volume) and in the Miocene development of the Danube Basin (Tari, this volume).

Ophiolitic Sutures

Unlike the West- and East-Mediterranean basins, which both still comprise undeformed oceanic crust, the Alpine orogen is characterized by several systems of ophiolitic bodies; these represent tectonized and obducted remnants of former Mesozoic oceanic basins, presently localized in often narrow suture zones within the allochthon. As outcropping ophiolitic nappes represent only fragments of these oceanic basins, they do not necessarily record the onset of sea-floor spreading in the respective basins, the timing of which must be

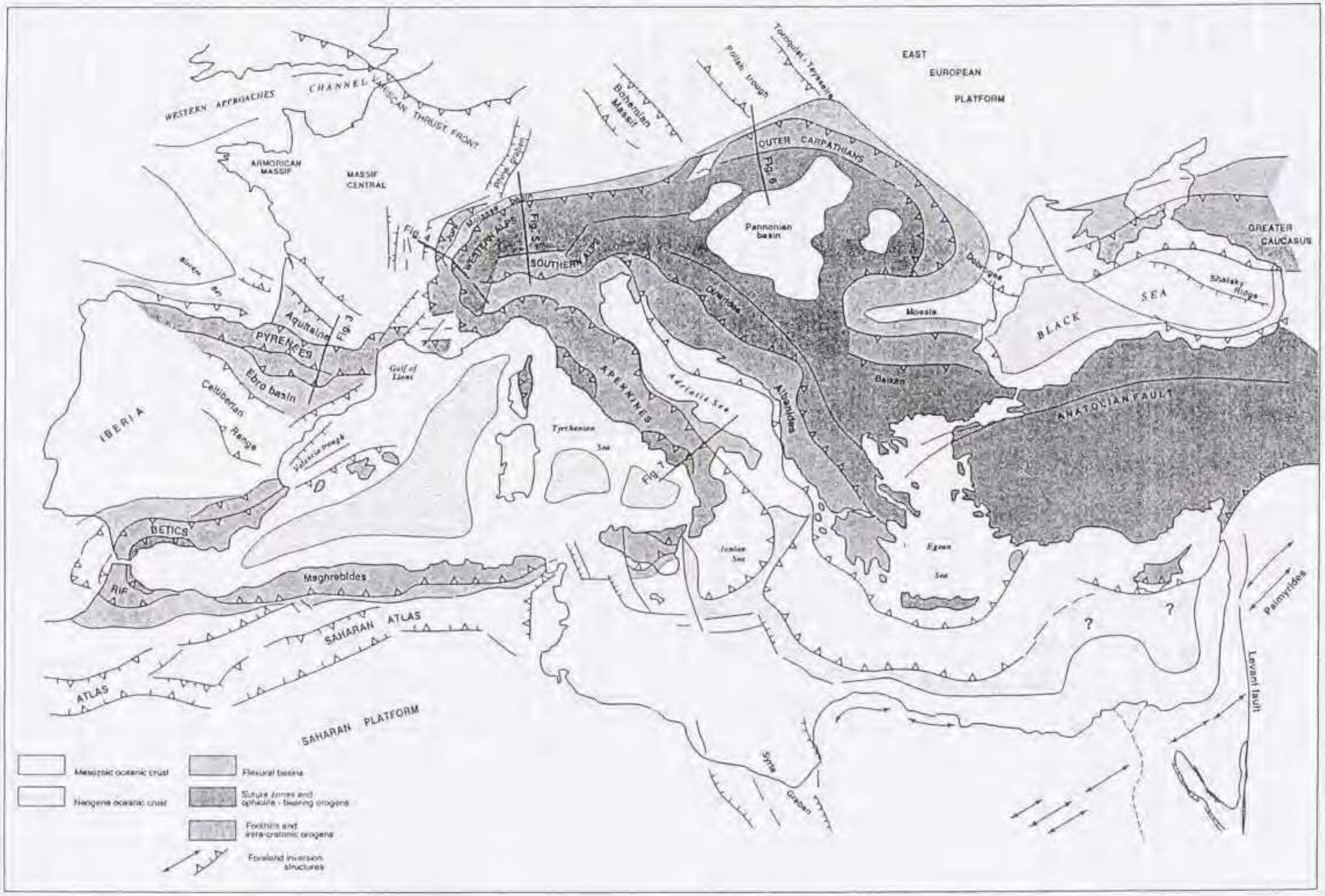

FIG. 1. Present distribution of oceanic sutures and relict oceanic domains within the Alpine orogen.

derived from the sedimentary record of the offsetting passive margin prisms, now involved in the Alpine nappes. Nevertheless, these ophiolitic suture zones relate to distinct segments of the former Tethys and record its step-wise opening (Fig. 1).

During the Late Permian-Early Jurassic initial break-up phase of Pangea, the Hallstatt-Meliata-Mures, Vardar and Sub-Pelagonian and possibly also the East-Mediterranean oceanic basins opened. To the east, this system of oceanic basins finds its continuation in the Izmir-Ankara-Erzincan and the Taurides ophiolitic belts. Opening of this system of oceanic basins resulted in partial separation of the Italo-Dinarides-Anatolia bock from Europe. With the Middle Jurassic development of a discrete transform/divergent plate boundary between Gondwana and Laurentia, opening of the Central Atlantic entailed a change in the opening kinematics of the Western Tethys; these were dominated during the Late Jurassic-Early Cretaceous by a major sinistral translation between Africa-Arabia and Europe, inducing progressive transtensional opening of the Alboran-Ligurian-Piemont-South Penninic Ocean. This was accompanied by decoupling of the Apulian terrane from Africa-Arabia and its complete isolation . At the same time new subduction systems developed in the Vardar-Hallstatt system of oceanic basins, governing their gradual closure. Early Cretaceous opening of the North Atlantic was paired with opening of the Bay of Biscay and of the North Penninic Valais Trough, which may equate to the intra-Carpathian Magura-Piennidic zone (Ziegler, 1988; Dercourt et al., 1993).

Some elements of the Alpine orogenic system, such as the Pyrenees and the Greater Caucasus, lack true ophiolitic sutures, despite the fact that they developed by closure of pre-existing smaller or larger oceanic troughs. In such fold belts ultramafic rocks may occur locally as narrow tectonic slices.

Closure of the different segments of the oceanic Tethys basins during the Alpine orogenic cycle was diachronous, also along the trace of the individual basins For example, in the Central Alps, the South Penninic Ocean was closed during the early Paleocene whereas in the Western Alps, final closure of the Piemont-Ligurian Ocean occurred only during the late Eocene (Ziegler et al., this volume).

Foreland Flexure and Residual Crustal Roots

Deep seismic profiling, including reflection and wide-angle surveys, gravity data, seismic tomography and modelling have provided a better insight into the crustal and lithospheric architecture of the various segments of the Alpine orogen.

Palaeomagnetic data, the inventory of seafloor magnetic anomalies and palinspastic reconstructions of the different segments of the Alpine orogen indicate that Late Mesozoic and Paleogene convergence of Africa-Arabia and Europe amounted to hundreds of kilometres and that it was accommodated by the subduction of equivalent amounts of oceanic and partly also continental lithospheric material (de Jong et al., 1993). This concept is supported by presence of long lithospheric slabs, penetrating the asthenosphere, which are imaged by the distribution of earthquakes and by seismic tomography, for instance beneath the active Calabrian and Aegean arcs as well as in the western Mediterranean (Spakman, 1990; Wortel et al., 1990; Spakman et al., 1993). Alternatively, major slab detachments probably occurred beneath the Alps, the Dinarides and the Carpathians during or soon after the Cretaceous-Paleogene episodes of intense shortening (von Blankenburg and Davies, 1995).

In contrast to major subduction zones, the Pyrenees are characterized by a limited crustal root only; this is in agreement with the relatively small lithospheric contraction during the late Senonian-Paleogene Pyrenean orogeny (about 110 km). Similarly, about 120 km of Oligocene to Recent subduction of the European continental lithosphere beneath the Alps, accounts for their present crustal root and a corresponding new subduction slab (de Jong et al., 1993; ECORS Pyrenees team, 1988; Choukroune et al., 1989; Frei et al., 1989; Roure et al., 1989, 1990; Pfiffner et al., 1988; Schmid et al., 1996). In both cases, conjugate foreland basins developed on either side of the orogen, although seismic and gravimetric data attest for strong asymmetries at depth (Bayer et al., 1989). Whereas in the Pyrenees the Iberian infra-continental mantle was progressively subducted northward, the European lithosphere was underthrusted to the southeast and south beneath the Western and Central Alps.

Other segments of the Alpine chain, such as the Languedoc-Provence, the Western and Eastern Carpathians and also parts of the Apennines, are characterized by limited crustal roots and a Moho which progressively shallows toward the internal zone of these orogens, corresponding to the Gulf of Lions, the Pannonian Basin and the Tyrrhenian Sea, respectively (Figs. 2 and 3; Tomek, 1993; Szafián et al., 1995). Frequently interpreted as a new Moho, this geometry of the crust-mantle boundary probably results from the extensional collapse of the internal parts of these belts, involving extensional reactivation of pre-existing compressional detachment horizons (thrust faults) and progressive denudation of the lower crust (metamorphic core complexes). Under post-orogenic conditions, this can entail rapid uplift and erosion of the external parts of the orogen and unflexing of the foreland lithosphere, as seen, for instance, in the northern Carpathians.

Foredeep basins flanking the Apennines and the southeastern Carpathians are extremely deep and contain up to 10 km of Miocene to Pliocene sediments. In contrast, the eastern Pyrenean and the West-Alpine forelands are almost devoid of syn-flexural sediments.

The width and depth of a flexural basin largely depends on the thickness and thermal regime of the foreland lithosphere, controlling its rheology, as well as on the loads which are exerted on it by the subduction slab and the overriding orogenic wedge (Watts et al., 1982; Kusznir and Karner, 1985; Deségaulx et al., 1991; Doglioni, 1993). Flexural down-bending of thick continental lithosphere can be accompanied by the development of an array of relatively small tensional, essentially basin-parallel normal faults at upper crustal levels, as evident in the German and Austrian parts of the Molasse Basin (Roeder and Bachmann, Zimmer and Wessely, this volume). If such a foreland crust is weakened by pre-existing faults which can be reactivated during its flexural deformation, strain may be concentrated on a few major faults which can have throws of the order of 1 km and more, as seen in the Ukrainian part of the Carpathian foredeep (Sovchik and Vul, this volume). Rapidly and deeply subsiding foredeep basins are generally characterized by strongly stretched and attenuated continental crust which is thinner and warmer than adjacent parts of the foreland. This accounts for the contrasted geometries of the western and eastern portions of the Aquitaine foredeep, and for the segmentation of the Periadriatic depressions in front of the Apennines or between the Dinarides and the Albanides (Royden et al., 1987; Deségaulx et al., 1991; Doglioni, 1993).

In some foreland basins, intra-plate compressional structures play an important role and, by their development, can either impede the development of a flexural basin or can cause partial or total destruction of a pre-existing flexural basin. Such structures can develop by inversion of pre-existing tensional basins, in which case they may involve the basement (i.e. Provence, Dauphiné; Roure and Colletta, this volume). Alternatively, activation of sedimentary detachment horizons within the foreland basin can cause the development of thin-skinned compressional structures, as seen in the Prerifaine chains of Morocco (Zizi, this volume), the South-Alpine Lombardian Basin (Ziegler et al., this volume), the Jura Mountains (Philippe et al, this volume) and also in the Apennine foredeep (Anelli et al., this volume).

Oblique Versus Orthogonal Collision and Strain Partitioning

Although Africa-Arabia converged with Eurasia since Senonian times in a north-south directed counter-clockwise rotational mode, sinistral motions between them, related to the opening of the Atlantic Ocean, decreased gradually and ceased at the transition from the Paleocene to the Eocene in conjunction with opening of the Norwegian-Greenland Sea. However, during the Oligocene and Miocene a dextral component is evident in their convergence pattern; this translatory movement probably persisted into Recent times, as indicated by earthquake focal mechanisms and neotectonic deformations (Ziegler, 1988, 1990).

During the Late Jurassic-Early Cretaceous opening phases of the Central Atlantic, sinistral motion between Africa-Arabia and Europe gov-

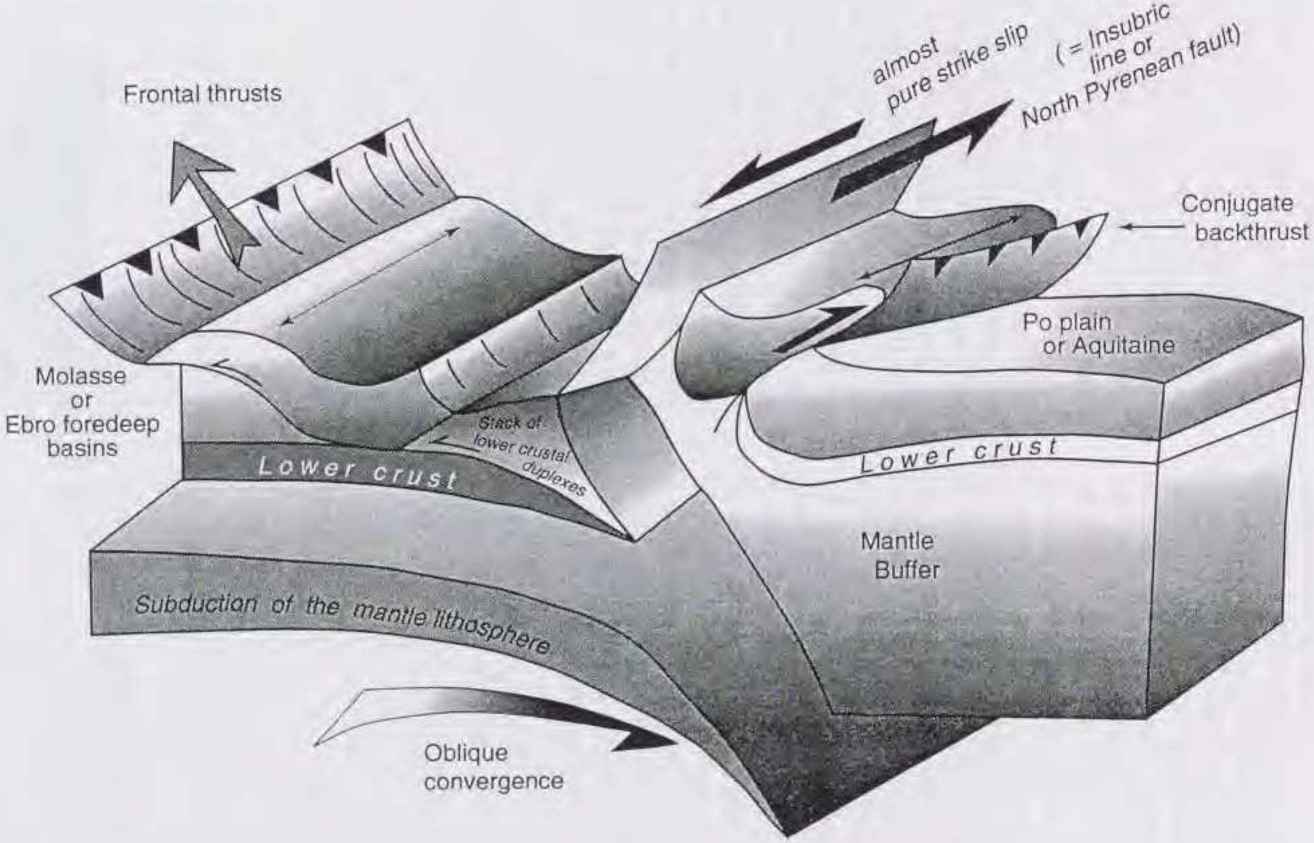

FIG. 2. Block diagram outlining the role of strain-partitioning in areas of oblique convergence or collision.

erned the closure of the Hallstatt-Vardar ocean system, rotation of the Italo-Dinarides-Anatolia block and its progressive incorporation into the Dinarides-Hellenides-Pontides orogenic system. With the Senonian onset of northward drift of Africa-Arabia and progressive opening of the Atlantic, these sinistral motions gradually decreased whereas increasing space constraints in the Western Tethys caused rapid westward propagation of subduction zones into the the domain of the Ligurian-Alboran Ocean. For instance, in the Alps, the Cretaceous orogenic cycle was characterized by northwest-directed mass transport whereas the Paleogene orogeny was dominated by north directed mass transport (Schmid et al., 1996). Paleogene progressive closure of the Tethys and increasing collisional coupling of the evolving orogen with its forelands, lateral block escapes and oblique motions played an increasingly important role. Suturing of Iberia to Europe was accompanied by the development of the left-lateral North Pyrenean Fault. Eastward directed Oligo-Miocene mass transport from the Alpine into the Carpathian domain, as a consequence of full-scale collision of the Adriatic indenter with Europe (Ratschbacher et al., 1991), was accompanied by left-lateral motions along the North Carpathian Pienniny Klippen belt and incipient right-lateral motion along the South Carpathian foothills (Fig. 1; Laubscher, 1992a; Ellouz and Roca, 1994). Miocene-Pliocene development of a system of right-lateral strike slip fault systems, including the South Atlas fracture system, the Insubric line of the Southern Alps, the intra-Dinarides Peri-Adriatic and the North Anatolian fault systems, may be partly related to the dextral translation of Africa-Arabia and Europe and partly to lateral mass redistribution in response to the massive indentation of Arabian and the Adriatic block (Ziegler, 1988).

However, as in still presently active transpressional orogens, such as the South Caribbean belt in Eastern Venezuela, or along the San Andreas Fault west of the San Joachin Valley, a strong strain partitioning occurred within most of the Alpine orogenic belts (Laubscher, 1992a; Passalacqua et al., 1995). Thus, the overall northwest- or northeast-trending collision zone between major plates was ultimately confined to the subducted lithosphere in the footwall, and to the hanging-wall mantel indenter (Fig. 2). In contrast, frontal accretion characterized the conjugate external thrust belts on both sides of the orogenic wedge, with major thrusts always paralleling the active plate boundary (see e.g. Gilmour and Mäkel, Le Vot et al., Philippe et al, this volume). Apparently, the oblique convergence component was largely absorbed within the orogenic wedge by strike-slip motions along, at shallow levels, sub-vertical faults. Such faults can strike normal to the overall convergence direction as e.g. the Insubric line of the Central Alps, or at a high-angle as e.g. the intra-Dinarides Peri-Adriatic line. Their orientation is largely controlled by the geometry of rigid indenters, such as the Apulian platform.

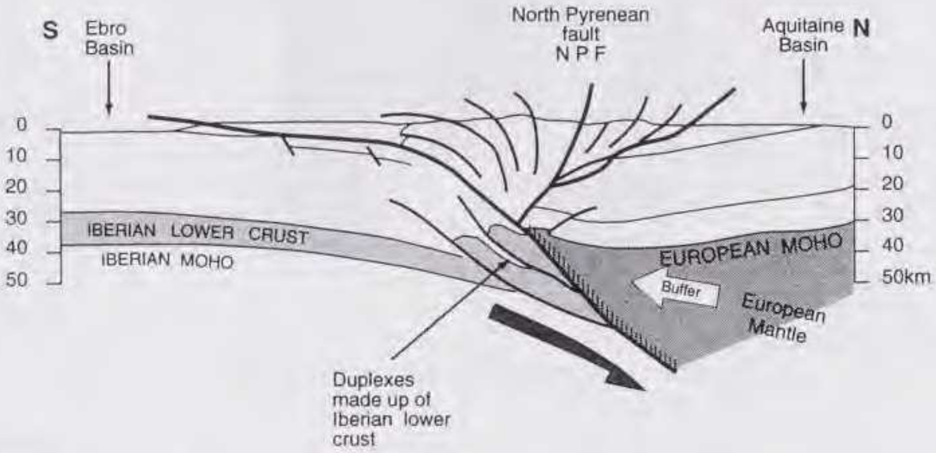

FIG. 3. Crustal section across the Pyrenees

RIFTING AND DEVELOPMENT OF PASSIVE MARGINS

Tethyan rifting initiated soon after the consolidation of the Variscan orogen at the end of the Westphalian (von Raumer and Neubauer, 1993). Development of the widespread, wrench- and rift-induced Permo-Carboniferous successor basins of Western and Central Europe Europe can be related to such processes as changes in the convergence pattern of Gondwana and Laurussia during the Allegenian phase of the Appalachian-Mauretanides orogen, to back-arc extension in response to roll-back of the Variscan subduction slab and its ultimate detachment from the lithosphere and to the onset of regional extension, controlling the break-up of Pangea (Ziegler, 1990, 1993).

In the Western Tethys domain, major crustal extension commenced, however, only after the Appalachian-Variscan suture between Gondwana and Laurussia had become inactive at the transition to the Late Permian (Ziegler, 1989; Stampfli and Pillevuit, 1993). Rifting activity accelerated during the Triassic, propagated westward and interfered in the Atlantic domain with the southward propagating Arctic-North Atlantic rift system (Ziegler, 1988). Step-wise opening of the different oceanic basins of the Western Tethys, resulting in the development of passive margins, as summarized above, is retraced in the palaeogeographic/palaeotectonic maps of Yilmaz et al. (this volume). We recall here only, that probably most of the Tethyan passive margins developed during the Triassic and the Middle Jurassic.

Variscan Inheritance and Localization of Tethys Rifts

The Triassic-Jurassic Gulf of Mexico-Central Atlantic-Western Tethys rift/transform system represents one of the major break-up axes of Permo-Triassic Pangea. Significantly, this break-up axis coincides to a large extent with the Appalachian-Variscan suture of Gondwana and Laurussia (Ziegler, 1990, 1993). Rheological considerations suggest that the orogenically destabilized lithosphere of this suture was considerably weaker than that of the flanking cratons (Cloetingh and Banda, 1992) and, as such, preconditioned the localization of this break-up axis.

In Western and Central Europe and the Western Tethys domain, the lithosphere was further weakened during the Stephanian-Autunian collapse of the orogenically thickened Variscan crust. Wrench- and extensional faulting, resulting in the uplift of core-complexes, was associated with the synkinematic intrusion of granites and the extrusion of alkaline and calc-alkaline magmas. This was presumably accompanied by the detachment of the subducted lithospheric slab(s), at least partial delamination of the deep lithospheric roots of the Variscan orogen and its corresponding uplift. Moreover, transtensional uplift of core-complexes and erosional unroofing of the crust was paralleled by upwelling of the asthenosphere and the interaction of mafic melts with the crust. With the termination of wrench activity at the transition to the Late Permian, cooling of the thermally destabilized lithosphere controlled crustal subsidence and regional transgressions. In time, the crust/mantle boundary re-equilibrated regionally at depths of about 35-40 km (Ziegler, 1990; Ziegler et al., 1995; Costa and Rey, 1995).

In the European Alpine foreland there is ample evidence of repeated Mesozoic reactivation of Permo-Carboniferous crustal discontinuities, in part guiding the localization of rifted structures, such as the Polish Trough (Ziegler, 1990). Deep reflection-seismic profiles show that Variscan compressional structures were only rarely reactivated during the Mesozoic rifting phases in the distal parts of the Alpine forelands.

For instance, the ECORS seismic profiles image beneath the conjugate Ebro and Aquitaine forelands of the Pyrenees south-verging Variscan structures (Servey Geologic de Catalunya, 1993). These were transected by Permo-Carboniferous wrench faults and apparently did not materially contribute towards the localization of Mesozoic extensional faults. In contrast, reactivation of south-verging Hercynian structures probably accounts for coaxial Alpine deformations along the southern flank of the Pyrenees (Deségaulx et al., 1990). On the other hand, the Mesozoic Bay of

Biscay rift zone appears to be superimposed on a major Permo-Carboniferous wrench zone.

Although the architecture of those parts of the Variscan orogen which were overprinted by Alpine deformations is still poorly known (von Raumer and Neubauer, 1993), it is evident that also these areas were affected by intense Permo-Carboniferous wrench tectonics and associated magmatism. It is likely that also in these areas reactivation of Permo-Carboniferous crustal discontinuities played a significant role in the localization of the Tethys rift systems.

Late Carboniferous coal-measures contained in Variscan foreland and successor basins, as well as coal-measures and lacustrine shale of the Stephanian-Autunian wrench-induced troughs, provide potential source-rocks in the pre-rift sedimentary sequences of the European foreland. Depending on their burial beneath the Tethyan passive margin sequence, or beneath syn-orogenic flexural sequences and the Alpine allochthon, such source-rocks can have locally preserved part of their petroleum potential and thus can contribute to effective petroleum systems, as for instance in the Jura Mountains and in the subthrust play of the Polish Carpathians (Bessereau et al., this volume).

Rifting and Development of Passive Margins

As discussed above, rifting activity in the Tethys domain spanned Permian to Early Cretaceous times and culminated in the step-wise opening of its constituent oceanic basins. Late Permian, Triassic and Early Jurassic rifting activity is well documented in the different parts of the Western Tethys (Stampfli and Pillevuit, 1993; Stampfli, 1996). During the Triassic, rifting activity propagated westwards and affected very wide areas around the future zones of crustal separation (Ziegler, 1988). In time, rifting activity concentrated on zones of future crustal separation, as seen for instance in the Southern Alps (Bertotti et al., 1993). From Mid-Jurassic to Early Cretaceous times, rift and wrench activity in the Western Tethys was governed by the sinistral translation of Africa-Arabia relative to Europe, in response to progressive opening of the Atlantic Ocean.

Earliest passive margins were associated with the opening of the Hallstatt-Vardar system of oceanic basins. Mid-Jurassic opening of the Alboran-Ligurian-Piemont-South Penninic ocean resulted in the development of a new set of passive margins. Late Jurassic-Early Cretaceous opening of the Bay of Biscay, the North Penninic and the Magura basins led to the development of yet an other system of passive margins.

Development of the different Tethys rift systems entailed a renewed destabilization of the asthenosphere-lithosphere system. Crustal extension was accompanied by variable levels of rift magmatism. As there is no obvious evidence for hot-spot activity, crustal extension was presumably of a "passive" nature, driven by far field stresses governing the break-up of Pangea (Ziegler, 1993, 1995a). The availability of pre-existing crustal discontinuities, which could be tensionally reactivated, favoured simple shear crustal extension and the development of upper and lower plate margins (Favre and Stampfli, 1992). Locally crustal stretching involved the activation of intra-sedimentary detachment levels; for instance, in the basin of Southeastern France, low-angle listric extensional faults, soling out in Carboniferous coal-measures or Triassic evaporites, account for decoupling of the sedimentary cover structures from the basement. Subsidence of grabens and half-grabens was accompanied by uplift of the rift shoulders and the development of rift-flank basins (Favre and Stampfli, 1992). Upon achievement of crustal separation, marginal graben systems became inactive and were incorporated into the newly formed passive margins.

The duration of the rifting stage of the different Tethys extensional systems is highly variable. For example, the Aquitaine-Bay of Biscay basin records some 130 Ma of intermittent rifting activity prior to its Mid-Aptian transtensional opening (Deségaulx and Brunet, 1990), whereas the Atlas troughs, after about 60 Ma of rifting activity, became inactive in conjunction with crustal separation in the Central Atlantic.

During much of Late Permian to Early Cretaceous times, large parts of the Tethys domain were dominated by carbonate shelves. Syn-sedimentary tectonics accounted for rapid lateral facies and thickness changes. Partly reefal or dolomitic shallow water carbonates were restricted to the rift flanks, the crests of tilted blocks and to little extended platforms, whereas shaly or cherty deeper water carbonates and shales were deposited, partly under anoxic conditions, in rapidly subsiding grabens and in sediment starved lagoons.

Triassic, Jurassic and Early Cretaceous syn-rift source rocks provide for an number of effective petroleum systems (Table 1).

How Passive Were the Tethys Margins

The present day Central Atlantic margins remained in a passive setting for 180 Ma. Also the Arabian Shelf had undergone a passive margin evolution for some 175 Ma before it became collisionally coupled during the Senonian with the evolving Zagros orogen. In contrast the passive margins of the Western Tethys had a relatively short life span. For instance, the eastern margin of the Italo-Dinarides block was incorporated into the Dinarides orogen about 100 Ma after the Vardar Ocean had opened (Frasheri et al., this volume). The Austroalpine margin, facing the South Penninic Ocean, remained in a passive setting for some 60 Ma before it was converted into an active margin during the Early Cretaceous. Intra-Senonian and Paleocene compressional deformation of the East-Alpine and North-Carpathian forelands occurred about 50 Ma after the Valais and Magura basins had opened (Kovac et al., 1993; Ziegler et al., this volume). On the other hand, the Pyrenean margin was only for some 25 Ma transtensionally "passive" before it was compressionally deformed (Le Vot et al., this volume).

In view of the opening kinematics of the Atlantic Ocean and of the Tethyan system of oceanic basins, controlling also the interaction of the different blocks delimited by the latter, many of the evolving Tethyan passive margins were repeatedly tectonically destabilized. This had repercussions on their thermal subsidence pattern and the resulting development of passive margin sedimentary prisms. Examples of tectonic destabilization of Tethyan passive margins are:

(1) Late Jurassic and earliest Cretaceous wrench activity in the Bohemian massif and southward adjacent areas in conjunction with a stress reorganization in the North Sea rift system (Ziegler, 1990)

stratigraphic age	basin type	source-rock type	petroleum provinces
Neogene	flexural foreland	diluted III biogenic gas	E. Molasse, Carpathians Peri-Adriatic Basin
Oligocene	flexural foreland	II and III	Carpathians, Caucasus E. Molasse
	syn-rift	?	Rhine G., Valencia T.
Albian-Turonian	passive margin	II	Apulian & Scythian Platf., Maghrebides
Late Jurassic	passive margin	II	Vienna Basin
	syn-rift	II-III	Aquitaine Basin
Middle Jurassis	passive margin	II	Kuban foredeep
Early Jurassic	passive margin	II	Albania, Epirus
	syn-rift	II	Sicily, S. Alps
Triassic	syn-rift	I-II	S. Alps, Apennine Siclily, Albanides
Late Carboniferous	flexural foreland	III	Permian Basin
Silurian	passive margin	I-II	S. Anatolian foreland

TABLE 1
Effective source rocks in Alpine Orogen and associated basins

(2) Early Cretaceous opening of the Valais Trough, disrupting the subsidence pattern of the European shelf bordering the South-Penninic trough which had begun to open during Mid-Jurassic times (Stampfli, 1993)
(3) Late Jurassic-Early Cretaceous wrench-induced deformation of the Moroccan shelf during the opening of the Central Atlantic and Alboran-South Penninic oceans (Favre and Stampfli, 1992)
(4) Early Cretaceous rifting in Libya and Egypt. It is likely that also thermal subsidence of the Italo-Dinarides block was influenced by its Early Cretaceous rotation.

The timing of incorporation of the different peri- and intra-Tethyan passive margin prisms into syn-orogenic flexural basins is also highly variable. Whereas during Cretaceous times progressively more internal units of the Italo-Dinarides Block were incorporated into the Hellenic-Dinarides foreland basin, the western shelves of this block were incorporated into the Apennine foredeep only during the Late Oligocene and Miocene (Frasheri et al., Anelli et al., this volume). A special case is presented by the Helvetic shelf of the Central and Eastern Alps which began to subside during the Eocene under the load of the advancing nappes; however, pre- or even syn-collisional stresses exerted on this shelf induced transpressional reactivation of pre-existing crustal discontinuities and profound disruption of its sedimentary cover. For instance, intra-Senonian and Paleocene inversion of the Polish Trough and the Bohemian Massif resulted in partial destruction of the passive margin prism of the East-Alpine and the North- and East-Carpathian forelands (Ziegler, 1990; Ziegler et al., 1995).

Correspondingly, the age, thickness and composition of the different peri- and intra-Tethyan passive margin prisms is highly variable. These passive margin prisms attained maximum thickness prior to their incorporation into flexural basins. Correspondingly, potential source-rocks of the syn-rift and passive margin sequences reached maximum sedimentary burial and started to generate hydrocarbons already prior to their subsequent burial beneath flexural foredeep prisms or the Alpine allochthonous units. In distal foreland areas, which escaped such burial, the syn-rift and passive margin sedimentary series preserved part of their petroleum potential (e.g. Aquitaine Basin, Le Vot, this volume).

The Tethyan passive margin sequences account for the source-rocks, reservoirs and/or seals of some of the most efficient petroleum systems identified within the external parts of the Alpine fold-and-thrust belts and their forelands (Table 1). Examples are the Early Jurassic Posidonia shales of the Albanian Ionian zone (Baudin and Lachkar, 1990; Frasheri et al., this volume) and the Aquitaine basin (Le Vot et al., this volume) and the Late Jurassic shales beneath the Vienna basin (Ladwein et al., 1991). Although numerous Cretaceous black-shale intervals have been reported from the peri-Tethyan passive margins, particularly from the Albian-Cenomanian and Turonian series of the Periadriatic domain, in Aquitaine or in the Carpathians (Le Vot et al., Stefanescu and Baltes, this volume), their efficiency is still questionable as only limited hydrocarbon accumulations could be directly correlated with them.

CONVERGENCE, COLLISION AND SUBDUCTION OF CONTINENTAL LITHOSPHERE

We recapitulate that in the Western Tethys initiation of and activity along subduction zones was controlled during the Late Jurassic-Cretaceous Pangea break-up phase by the sinistral translation of Africa-Arabia and Europe, and during Senonian to Recent times by their Alpine convergence. As the European and Africa-Arabian passive Tethys margins were not parallel, and as the Iberian and the Italo-Dinarides microcontinents acted as indenters during the Alpine cycle, collisional events were diachronous (Tapponnier, 1977). Preservation of remnants of Tethyan oceanic crust in the Ionian Sea and in the Eastern Mediterranean illustrates that continent-to-continent collision has not yet occurred along the entire trace of the Tethys suture (Fig. 1).

The onset of subduction processes can be stratigraphically dated by the sedimentary record of accretion prisms, or petrologically and radiometrically by arc volcanism and HP/LT metamorphism. The collision of an arc trench system with a passive margin, marking the transition from subduction of oceanic to continental lithosphere (B-type to A-type subduction), is reflected by the rapid subsidence of the foreland crust and by the deposition of syn-orogenic flysch series on top of the passive margin sequence. However, it must be realized, that initial collision zones are generally deeply buried beneath orogenic wedges and in part have been subducted to great depths. Only in rare cases will subduction progradation, or perhaps extension, entail the exhumation of an earlier active subduction zone and render it accessible to surface observation (e.g. Tauern window; Froitzheim et al., 1996). These criteria have been applied in the construction of palaeogeographic/palaeotectonic maps retracing the evolution of the Alpine orogen (Ziegler, 1988; Dercourt et al., 1993; Stampfli, 1996; Yilmaz et al, this volume).

Not only the timing of orogenic activity is highly variable in the different segments of the Alpine system but also the amount of crustal shortening, including subduction of oceanic crust and post-collisional subduction of continental lithosphere. In this respect, the intensity of collisional coupling of the evolving orogenic wedge with its foreland, as well as the availability of a thick sedimentary cover which could be detached from the foreland crust, played an important role in the architecture of the different fold-and-thrust belts forming the Mediterranean-Alpine orogen. In the following selected examples are discussed which are further analyzed in the different chapters of this volume.

Pyrenees

The Pyrenees evolved in response to late Senonian-Paleogene transpressional closure of the wedge-shaped inter-continental Bay of Biscay Basin; this was induced by the build-up of far-field compressional stresses related to the convergence of Africa with Europe, causing clock-wise rotation and escape of Iberia. Crustal shortening across the Pyrenees amounts to some 110 km (Roure et al., 1989; Deségaulx et al., 1990).

Their axial zone is characterized by asymmetrically north- and south-verging, thrusted basement blocks. Their northern foreland, the Aquitaine Basin, is characterized by partly reactivated extensional fault bocks and thin skinned thrust sheets which are detached from the basement at the level of Triassic evaporites (Le Vot et al., this volume). The southern Pyrenean external zone is characterized by thin skinned thrust sheets, detached from their basement at the level of Triassic evaporites; the basement cores of these sheets form part of the internal structure of the Pyrenees (Vergés and Munoz, 1990). The Pyrenean orogeny is coeval with orogenic activity in the Betic Cordillera. Paleogene compressional stresses exerted on cratonic Iberia caused reactivation of Permo-Carboniferous and Mesozoic crustal discontinuities, controlling inversion of the Celt-Iberian and Catalonian Coast ranges and upthrusting of the Sierra Guadarrama basement block (Ziegler, 1988; Salas and Casas, 1993; Ziegler et al., 1995).

Commensurate with the amount of crustal shortening achieved across the Pyrenees, they are characterized by a limited north-verging crustal root and no pronounced lithospheric root; they lack a syn-orogenic magmatism (Fig. 3; Spakman, 1990; Servey Geologic de Catalunya, 1993).

Whereas the northwestern, deep foreland basin of the Pyrenees hosts the major Aquitaine hydrocarbon province (Le Vot et al., this volume), its eastern shallower parts and the southern foreland contain no significant hydrocarbon accumulations.

Western Alps

From plate reconstructions, the total crustal shortening achieved across the Western Alps is estimated to amount to some 400 km (Platt et al., 1989). This involved Late Cretaceous activation of the Apulian margin, Late Cretaceous-Paleogene closure of the oceanic Piemont, Eocene closure of the Valais basins (Froitzheim et al., 1996) and sub-

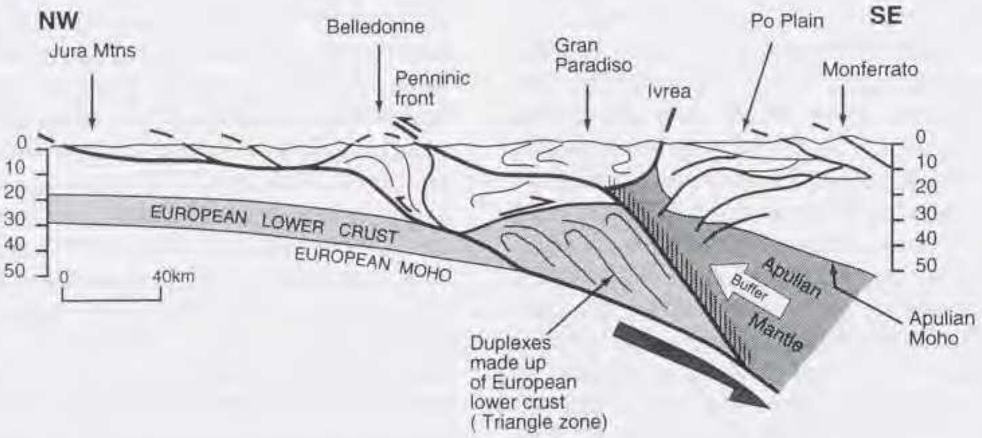

FIG. 4. Crustal section across the Western Alps.

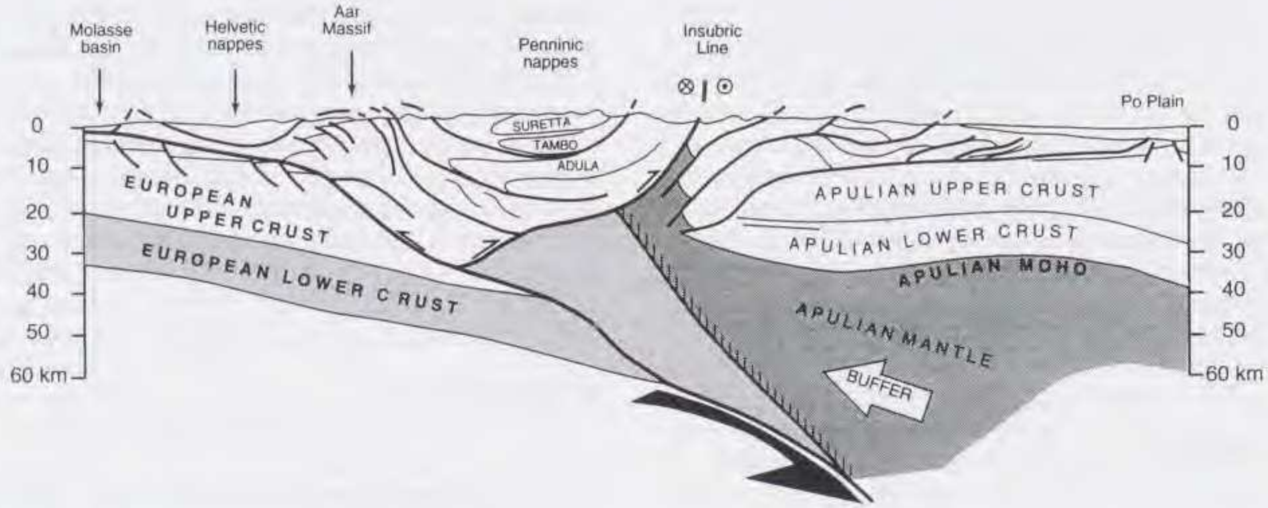

FIG. 5. Crustal section across the Central Alps

sequent imbrication of the European foreland crust, resulting in the uplift of the external Pelvoux, Belledonne and Mont Blanc crystalline massifs (Fig. 4).

Nappes derived from the Apulian margin occupy the northeastern part of the Western Alps (Sesia-Lanzo and Dent Blanche nappes). The internal Schistes Lustrés nappe, containing ophiolites, was derived from the Piemont Ocean. The Valais Trough and the Briançonnais were deformed into a system of west- and east-verging nappes, respectively, which overrode the passive foreland margin, causing late Eocene-Oligocene subsidence of a flexural foreland basin. Subsequent intense coupling of the orogenic wedge with the foreland is evident by compressional reactivation of Mesozoic tensional faults on the distal foreland margin, the step-wise imbrication of the foreland crust and detachment of the passive margin series from their basement. By this process the earlier developed foreland basins was largely destroyed. During late Eocene to Miocene times, the West-Alpine foreland was transected by a system of grabens which form part of the European Cenozoic rift system (Ziegler, 1994b). During Miocene and Pliocene times, Mesozoic and Cenozoic extensional basins in the foreland of the Western Alps were inverted, causing disruption of the Mesozoic proximal passive margin sedimentary prism; moreover thrusting propagate into the domain of the Jura Mtns. (Roure et al., 1990; Roure and Colletta, Philippe et al, this volume).

Commensurate with the dominantly west-vergence of the external Western Alps, their up to 60 km deep crustal root (Laubscher, 1992b) is located under their eastern, internal parts. Moreover, seismic tomography images an about 175 km deep lithospheric root, located beneath the western Po Plain and an apparently detached, east-dipping subduction slab (Spakman, 1990). The Western Alps are devoid of subduction related magmatism. Their evolution reflects increasing collisional coupling of the orogenic wedge with the European foreland in which contemporaneous inversion structures developed as far away as in the Western Approaches and the Celtic Sea (Ziegler, 1990; Ziegler et al., 1995).

The external parts of the Western Alps and their foreland contain no significant hydrocarbon accumulations. Sub-thrust plays are areally restricted due to the limited extent of the foreland beneath the frontal thrusts.

Central Alps

The Central Alps evolved by Late Cretaceous and Paleogene closure of the larger South Penninic and the smaller North Penninic Valais oceanic basins. The total amount of crustal shortening achieved across the Central Alps is in the range of 500 to 550 km (Fig. 5; Schmid et al., 1996; Ziegler et al., this volume).

The Central Alps are characterized by major, north-verging, partly basement cored nappes. The Austroalpine nappes were derived from the southeastern margin of the South Penninic Ocean. The Penninic nappes derive from the North and South Penninic troughs and the Briançonnais block, separating them. The sedimentary Helvetic nappes were derived from the northern, European shelf; their basement core is represented by the Gotthard Massif and the lowermost Penninic nappes. Mio-Pliocene uplift of the external Aar Massif, entailing deformation of the overlaying stack of nappes, was partly contemporaneous with the development of the Jura fold-and-thrust belt. The Southern Alps consist of a south-verging internal stack of basement imbrications and an external, thin-skinned thrust belt.

End Cretaceous to early Paleocene closure of the South Penninic trough was accompanied by large radius deformation of the Helvetic shelf, causing erosion of much of its Cretaceous sedimentary cover. Late Eocene closure of the North Penninic trough was followed by flexural subsidence of the Helvetic shelf under the load of the advancing Austroalpine, Penninic and Helvetic nappes; the Helvetic nappes consist of sediments which were detached from the foreland crust. Post-collisional indentation of Apulia, amounting to some 120 km, caused overthickening of the orogenic wedge. This gave rise to Oligocene backfolding and -thrusting along the Insubric line, Mio-Pliocene step-wise imbrication of the northern and southern foreland crust and ultimately thrust propagation into the conjugate flexural foreland basins, causing their partial destruction. Post-collisional crustal shortening was accompanied by the subduction of continental lithospheric material.

South-directed underthrusting of the European foreland gave rise to the development of a some 60 km deep crustal root beneath the southern part of the Central Alps and a 175 km deep lithospheric root located beneath the northern parts of the Po Plain (Spakman, 1990). Oligocene detachment of an earlier formed subduction slab from the lithosphere was accompanied by the intrusion of partial melts derived from the mantle-lithosphere (von Blankenburg and Davies, 1995).

The South-Alpine external, thin skinned thrust belt evolved out of a Triassic extensional basin, a superimposed passive margin prism and a late Oligocene-mid-Miocene flexural foreland basin; it hosts significant hydrocarbon accumulations (Anelli et al., this volume). The northern, Molasse foreland basin contains a thick syn-orogenic clastic wedge which rests on a relatively thin passive margin sequence. This basin is internally little deformed, extends only some 25 km beneath the Alpine nappes to the frontal basement imbrications of the Aar massif and is limited to the north by the Jura fold-and-thrust belt. The Molasse Basin has a very limited hydrocarbon potential (Ziegler et al., Philippe et al., this volume).

Eastern Alps

In contrast to the Central Alps, the Eastern Alps are characterized by an autochthonous basement which extends from the northern thrust front for at least 60 and perhaps as much as 100 km under the stack of Austroalpine nappes (Zimmer and Wessely, Tari, this volume). The eastward disappearance of major Helvetic nappes, involving European passive margin sediments, is striking. As Penninic nappes play a subordinate role in the architecture of the Eastern Alps, it is assumed that the Valais Trough terminates to the east or merges with the South Penninic Trough. In this context, Froitzheim et al. (1996) propose that the crystalline core of the Tauern window is formed by European crust and, as such, is not equivalent to the Briançonnais, as commonly suggested (Tollmann, 1985).

Evolution of the Eastern Alps involved Late Jurassic closure of the Hallstatt and Cretaceous closure of the Penninic oceans. Cretaceous mass transport was northwesterly directed. Profound late Senonian and Paleocene disruption of the European passive margin shelf, involving transpressional reactivation of Permo-Carboniferous and

FIG. 6. Crustal sections across the Carpathians, imaging the changes from collision to back-arc extension or collapse (after Roure et al., 1996).

Mesozoic crustal discontinuities and ensuing uplift and erosion (Ziegler, 1990), presumably reflects initial intense coupling between the evolving orogenic wedge and its foreland. During the Paleogene the Austroalpine nappes were thrusted over the foreland crust; this was accompanied by the flexural subsidence of the eastern Molasse basin, which is characterized by an array of syn-flexural tensional faults. By early Miocene times, the sedimentary Austroalpine nappes had arrive near their present location. During the emplacement of the East-Alpine stack of nappes, the orogen was apparently mechanically decoupled from the foreland, as indicated by the absence of compressional foreland structures. Paleocene destruction of the Mesozoic passive margin prism, particularly in areas located to the south of the Bohemian massif, is held responsible for the eastward disappearance of the Helvetic nappes.

The small remnant foreland basin of the Eastern Alps hosts several petroleum systems. These are tied to Mesozoic and early Oligocene oil source-rocks and to biogenic gas generated in the Oligocene and early Miocene deeper water clastic series of the foreland basin fill. The subthrust play of the Eastern Alps has to contend with considerable reservoir and structural risks, deep objectives and topographic difficulties. The sedimentary allochthon contains important hydrocarbon accumulations beneath the Vienna Basin; elsewhere its hydrocarbon potential has as yet to be proven (Roeder and Bachmann, Zimmer and Wessely, this volume).

Northern and Eastern Flysch Carpathians

The Northern and Eastern Carpathians consist of a stack of sedimentary nappes, involving Early Cretaceous to Miocene flysch series which are thrusted over the foreland. The latter extends at least some 75 km under this orogenic wedge, which accounts for at least 250 km of shortening (Fig. 6). The ophiolite bearing Pienniny Klippen zone marks the internal boundary of the Flysch Carpathians, in which the involvement of passive margin sediments remains conjectural (Sandulescu, 1984; Roure et al., 1993; Bessereau et al., Sovchik and Vul, Dicea, this volume).

The Flysch Carpathians evolved in response to Mid-Cretaceous and Cenozoic south and westward subduction of the oceanic Magura-Piennide basin and eastward displacement of the intra-Carpathian North Pannonian, Tisza and Dacides blocks; these record Late Jurassic and Early Cretaceous orogenic events related to the closure of the Vardar-Hallstatt Ocean (Sandulescu, 1984; Csontos et al., 1992; Stefanescu and Baltes, this volume).

The passive margin sedimentary prism of the North- and East-Carpathians forelands was disrupted by the late Senonian and Paleocene deep inversion of the Polish Trough (Ziegler, 1990) and the Early Cretaceous inversion of the Dobrogea Trough (Belov et al., 1987). These features appear to link up beneath the Eastern Carpathians. Correspondingly, large parts of the autochthonous foreland beneath the Flysch Carpathians lack a thick passive margin prism which otherwise could have been detached from its basement during the Late Cretaceous and Cenozoic phases of the Carpathian orogeny. Reflection-seismic data show that flexural subsidence of the autochthonous foreland was accompanied by major normal faulting. Moreover, they image mild compressional deformation of the autochthonous basement beneath the internal parts of the Flysch Carpathian accretionary wedge; however, major basement structures of the Aar Massif type are lacking (Roure et al., 1993, Sovchik and Vul, Dicea, this volume).

Roll-back of the subducted oceanic slab and its dehydration is tracked by a chain of mid-Miocene to Pliocene calc-alkaline volcanics, paralleling the Klippen zone (Szabó et al., 1992). Deep reflection profiles through the North-Carpathians image the steeply south dipping European foreland crust (Tomek, 1993). The absence of post-Paleocene compressional foreland structures and the presence of only minor compressional basement structures beneath the Flysch Carpathians suggest that coupling between the orogenic wedge and its foreland was at a low level. Post-Oligocene development of the Flysch Carpathians was accompanied by the collapse of the Pannonian Basin in their hinterland (Royden and Horváth, 1988; Tari et al., 1992).

The Flysch Carpathians and their foreland host important petroleum systems. The most important one is related to the Oligocene Menilite shales; a second potential petroleum system is related to Cretaceous black-shales. Jurassic and even Palaeozoic source-rocks have locally contributed hydrocarbons (Bessereau et al., Brzobohaty et al., Stefanescu and Baltes, Dicea, this volume).

Peri-Adriatic Thrust Belts

The stable Adriatic (Apulian) platform is flanked to the east by the Dinarides-Albanides and to the west by the Apennines. Whereas in the Dinarides-Albanides orogenic activity commenced during the Late Jurassic and persisted variably into Miocene and Pliocene times, the Apennines evolved essentially during Neogene times (Frasheri et al., Anelli et al., this volume).

The west-verging **Albanides** are characterized by thin skinned thrust sheets which are detached from their autochthonous basement at the level of Triassic evaporites. These thrust sheets involve a thick Triassic-Jurassic passive margin sequence, dominated by carbonates, and Cretaceous to Paleogene flysch series which grade to the west into platform carbonates. Mio-Pliocene molasse series are involved in the most external zone. Westward progression of the flysch facies through time describes the gradual advance of the orogenic front and the migration of the flexural foreland basin. The up to 14 km thick Mirdita ophiolite nappe forms the orogenic lid of the Albanides. These ophiolites, which presumably represent the oceanic crust of Sub-Pelagonian trough, were obducted during the Late Jurassic closure of the Vardar system of oceanic basins. The autochthonous foreland crust extends essentially unbroken from the thrust front of the Albanides at least 100 km under their internal nappes

The external, Ionian zone of the Albanides host a major hydrocarbon province which derives its charge from multiple Mesozoic source-rocks (Frasheri et al., this volume).

In contrast to the long lived Albanides, the **Apennines** are a young orogenic belt which evolved only during late Oligocene to Plio-Pleistocene times. The Apennines are characterized by major sedimentary nappes; these involve Triassic to Paleogene syn- and post-rift shallow-water and pelagic series and Oligocene to Miocene flysch, deposited in an eastward migrating foreland basin. The flysch nappes are detached from their substratum. An ophiolitic nappe, or rather an ophiolitic mélange, is only locally preserved along the Tyrrhenian coast (Liguride units). The external flysch nappes override a thick parautochthonous and autochthonous Triassic to Paleogene sedimentary sequence, consisting predominantly of platform and pelagic carbonates (Fig. 7).

Following Paleogene closure of the Alboran-Ligurian-Piemont Ocean, the Apennines evolved in response to Oligocene and younger westward underthrusting and subduction of the Adriatic foreland. The flysch facies mirrors the progressive eastward migration of the flexural foreland basins and the gradual incorporation of its proximal parts into the evolving orogenic wedge (Ricci Lucchi, 1986). The most internal units of the Apennines are formed by Ligurides, representing the sedimentary fill of the Ligurian-Alboran Basin, and the basement involving Calabria-Peloritani nappes which are of uncertain origin. The main elements of the allochthon are derived from the distal parts of the Apulian platform which were separated from its main parts by the deep-water Lagonegro trough. Emplacement of these sedimentary nappes was accompanied by partial detachment of the autochthonous sedimentary cover of the Apulian platform, its imbrication and by in-sequence thrust propagation into the Adriatic Sea (Anelli et al., this volume). There is only little evidence for involvement of the Apulian crust in the orogenic edifice of the Apennines (Ponziani et al., 1995); correspondingly, the orogenic wedge and the foreland crust were largely mechanically decoupled during the Apennine orogeny.

Substantial supra-crustal shortening, evident in the Apennines, was apparently compensated by the subduction of continental lithosphere, giving rise to extensive magmatic activity along the western margin of Italy from mid-Miocene times onward. Steepening and roll-back of the subducted lithospheric slab is held responsible for contemporaneous back-arc rifting and the gradual opening of the Tyrrhenian Sea (Spakman et al., 1993; Serri et al., 1993; Doglioni, 1993).

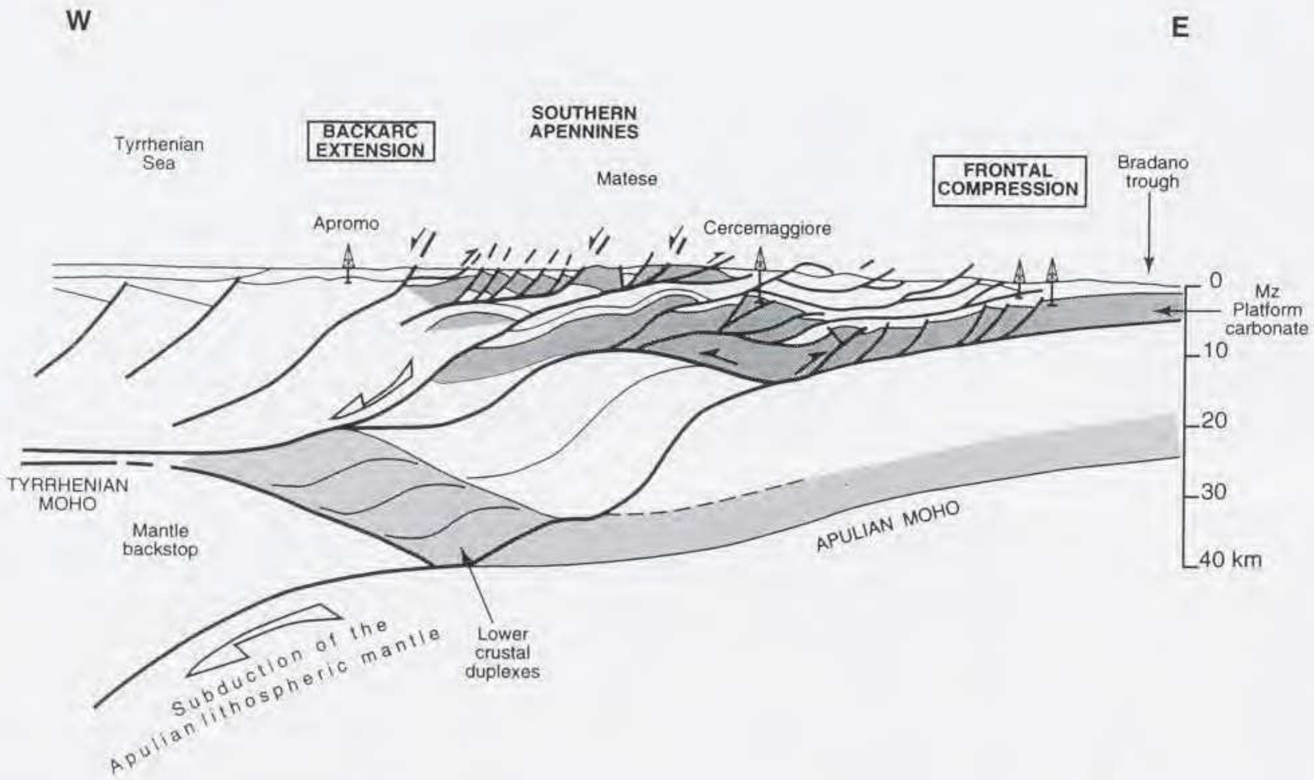

FIG. 7. Crustal section across the Apennines imaging the changes from collision to back-arc extension or collapse (after Roure et al., 1996).

The Apennines and their foreland basin host important petroleum systems which are related to Triassic and Jurassic source-rocks, deposited during the syn-rift stage. Secondary petroleum systems are related to the passive margin sequence and the syn-orogenic flexural basin. The latter contains major amounts of biogenic gas (Anelli et al., this volume).

East-Taurus Foothills Thrust Belt

The foothills of the eastern Taurus orogenic belt consist of a 30 to 40 km wide zone characterized by south-verging thin-skinned thrust imbricates, cored by Albian-Campanian shelf carbonates which were detached from the autochthonous Palaeozoic sedimentary cover of the Arabian Shield. To the north this thrust belt is limited by ophiolite and matamorphic nappes. Its southern foreland is characterized by a broad belt of intraplate compressional structures. This thrust belt developed during the Late Senonian to Eocene collision and of the North-Arabian passive margin with the Taurides arc-trench system (Yilmaz, 1993; Gilmour and Mäkel, this volume).

The North-Arabian passive margin developed during the Late Triassic with the opening of the Tethys Ocean. Its passive margin sequence spans Jurassic to Campanian times; it is interrupted by a major Early Cretaceous hiatus which truncates Jurassic strata to the north. Development of a flexural foreland basin commenced during the late Senonian and was accompanied by the obduction of the ophiolitic nappes and imbrications of the Cretaceous passive margin series. The external thin-skinned thrusted structures are sealed by Paleocene and younger series which were gently folded during the late Eocene. Eocene and Miocene continued thrusting was confined to the internal zones of the orogen and was accompanied by the closure of remnant oceanic basins. Miocene(?) foreland compression caused reactivation pre-existing crustal discontinuities, resulting in the upthrusting of foreland structures at distances of over 100 km to the south of the Alpine trust front.

The external, thrusted structures of the Taurus foothills are charged with hydrocarbons generated by Silurian shales of the autochthonous Arabian foreland, forming part of the Tethyan pre-rift sequence (Gilmour and Mäkel, this volume).

To round-off this pallet of diversified structural styles of the Alpine chains, attention is drawn to the paper by J. Flinch (this volume) who describes the gravitational collapse of the external accretionary prism of the Rif-Betic Cordillera arc which spilled over the Atlantic continental margin of Morocco and Iberia, forming the Gibraltar allochthon.

ALPINE FORELANDS

During the Late Cretaceous and Cenozoic phases of the Alpine orogeny, both the European and the Africa-Arabian forelands record a sequence of intra-plate deformations which caused drastic changes in their structural and palaeogeographic evolution.

Micro-tectonic analyses indicate that the trajectories of principal horizontal compressional stress axes affecting the European and Africa-Arabian platforms changed repeatedly during Late Cretaceous and Cenozoic times (Letouzey and Trémolières, 1980; Bergerat, 1987; Müller, 1987; Blès et al., 1989; Lacombe et al., 1990); this can be related to changes in their convergence pattern. Moreover, from late Eocene onward, gradual development of the Red Sea-Suez-Libyan-Pelagian Shelf and Rhine-Rhône-Valencia-Trans-Atlas rift systems was broadly contemporaneous with compressional intra-plate deformations. This is interpreted as reflecting the interference between stress systems related to the late phases of the Alpine collision and stresses related the gradual assertion of a new tensional kinematic regime, governing a fundamental plate-boundary reorganization, which may ultimately lead to the break-up of the present continent assembly (Ziegler, 1988, 1990, 1994b; Ziegler et al., 1995).

Intra-plate Compression

During the Late Cretaceous and Cenozoic, intra-plate compressional stresses reactivated a broad spectrum of tensional and transtensional Mesozoic and Palaeozoic basins in Europe and in Africa-Arabia, causing their inversion (Fig. 1). At the same time there are indications for broad buckling of the lithosphere, such as Plio-Pleistocene accelerated subsidence of the North Sea basin, uplift of the Fennoscandian Shield and Neogene isolation of the Paris Basin (Kooi et al., 1989; Ziegler, 1990; Ziegler et al., 1995).

In Europe, inversion structures and upthrusted basement blocks occur within a radius of up to 1500 km from the thrust front of the Alpine orogen. Late Cretaceous and Paleogene inversion features are located in the northern and northwestern foreland of the Alps and in the foreland of the Pyrenees, whereas Eocene and younger inversion structures are located in the foreland of the Western Alps. (Ziegler, 1987, 1990; Roure and Colletta, this volume).

In northern Africa, main intra-plate compressional structures evolved by latest Cretaceous and Eocene inversion of the Triassic Atlas rift system. (Casero and Roure, 1994; Zizi, this volume). The Saoura-Ougarta chain is a Palaeozoic rift which was inverted during the Permo-Carboniferous and underwent a second Alpine inversion during the Eocene (Ziegler, 1988).

On the Arabian craton, the Sinai arc, consisting of the Negev and the Palmyrides fold belts, represents a major inversion feature. The Palmyrides developed by inversion of a Permo-Triassic aborted rift. First mild compressional deformations occurred at the end of the Cretaceous; the major Mio-Pliocene phase of basin inversion involved transpressional deformations in response to NNW-SSE directed compression. Inversion of the Palmyra trough was contemporaneous with the thrusting phases in the East-Taurus orogenic belt and early movements along the Dead Sea wrench fault (McBriden et al., 1990; Chaimov et al., 1993). Transpressional deformation of the Negev fold belt is mainly late Senonian in age; minor inversion movements continued into the Miocene (Quennell, 1984; Moustafa and Khalil, 1995).

Basically we recognize two phases of prevailing intra-plate compression. The first phase is related to initial collisional coupling between a nascent orogen and its foreland (e.g. Carpathian and East-Alpine foreland). Such deformations may be controlled by the crustal configuration of the respective passive margin (upper or lower plate, availability of a thick passive margin prism or the lack thereof), the rheological characteristics of the oceanic lithosphere separating the accretionary wedge from the respective passive margin and the rate of their convergence. The second phase of foreland compression is related to lithospheric overthickening of the orogenic wedge and to resulting thrust propagation into the foreland (e.g. West and Central Alpine foreland). Processes governing the coupling and decoupling of an orogenic wedge and its foreland are, however, still poorly understood (Ziegler et al., 1995).

Inversion can have severe repercussions on the hydrocarbon habitat of a basin, mainly by reversing its subsidence pattern, by re-configuration of pre-existing structural traps and profound erosion, resulting in the loss of hydrocarbons to the surface. However, partly inverted basins can host important hydrocarbon provinces such as those of the Lower Saxony and West Netherlands basins (Ziegler, 1990, 1995b).

Cenozoic Rift Systems

Whereas lateral escape of, for instance, the Intra-Carpathian blocks, rotation of microplates, such as the Corsica-Sardinia block, and progressive retreat of subducted slabs in the Tyrrhenian Sea and the Aegean arc controlled the distribution of Neogene extensional structures within the frame of the overall compressional Alpine system of fold-and-thrust belts, late Eocene and younger development of the Rhine-Rhône and the East-African-Gulf of Suez-Libyan-Pelagian Shelf rift systems cannot be directly linked to the evolution of the Alpine orogen (Fig. 1).

The Cenozoic rift system of Western and Central Europe extends from the shores of the North Sea over a distance of some 1100 km into the West-Mediterranean domain; from there an alkaline volcanic chain projects southwestwards across the Alboran Sea, the Rif fold belt and the Atlas ranges to the Atlantic coast and to the Cape Verdes Islands. Including this volcanic chain, the entire rift system has a length of 3000 km. This rift system began to evolve during the middle and late Eocene in the European Alpine foreland and propagated during the Oligocene northward and southward. In the western Mediterranean, crustal extension culminated, after a rifting period of only 7 Ma, in Miocene crustal separation and the opening of the oceanic Algero-Provençal Basin; this involved a counter-clockwise rotation of the Corsica-Sardinia block (Torné et al., Vially and Trémolières, this volume). During Miocene and Plio-Pleistocene times, tectonic and partly also volcanic activity persisted along the different segments of this mega-rift system, albeit under changing regional stress regimes. Development of the Cenozoic rift system of Western and Central Europe was contemporaneous with the Eocene and later phases of the Alpine orogeny, during which the northwestern Alpine foreland was repeatedly subjected to horizontal intra-plate compressional stresses, causing inversion of Mesozoic extensional basins at considerable distances from the Alpine thrust front. The southern elements of the European Cenozoic rift system cross-cuts the Alpine chains of the western Mediterranean domain.

Viewed on a broader scale, evolution of the West and Central European Cenozoic rift system was broadly contemporaneous with the development of the East African-Red Sea, Libyan and Pelagian Shelf rift systems; its Neogene development was paralleled by back-arc extension governing the subsidence of the Pannonian Basin and the Aegean, Tyrrhenian and Alboran seas. As such the Rhine-Rhône-Valencia and the Red Sea-Libyan-Pelagian Shelf rift systems can be considered as forming part of the Neogene Alpine-Mediterranean collapse system (Ziegler, 1988, 1990). In this context, Neogene progressive eastward escape of Apulia and Sicily relative to North African may have contributed to the evolution of the Pelagian rift system (Casero and Roure, 1994).

However, considering the dimensions of the West European-West African and the East-African-Red Sea-Libyan rift systems, it is hardly conceivable that such major rifts developed solely in response to the Alpine collision. More likely, they form part of a new break-up system which may culminate in the disruption of the Alpine plate assembly (Ziegler, 1994b).

The European Cenozoic rift system hosts the Rhine Graben and Valencia Trough hydrocarbon provinces; whereas the former relies exclusively on syn-rift source-rocks, the latter relies on a combination of syn- and pre-rift source-rocks (Ziegler, 1995b, Torné et al, this volume). The major Gulf of Suez hydrocarbon province relies exclusively on Late Cretaceous pre-rift source-rocks (Ziegler, 1995b). The hydrocarbon charge of the Pannonian system of back-arc basins is related to a combination of syn- and pre-rift source-rocks. Uplift of major rift domes, such as those associated with the Rhine Graben and the Red Sea, causes disruption of the pre-rift platform sedimentary sequences and changes the hydrodynamic setting of the remnant rift flank basins (e.g. Paris Basin).

PETROLEUM SYSTEMS OF ALPINE FORELANDS AND EXTERNAL THRUST BELTS

The complex geodynamic and tectonic evolution of the Peri-Tethyan platforms and the subsequent Alpine development of the European-Africa-Arabian plate boundaries have conditioned both the distribution and maturation history of potential source rocks in the conjugate forelands as well as within the Alpine orogen and its successor basins.

Pre-Orogenic Versus Syn-Orogenic Source Rocks

Palaeozoic source-rocks of the pre-rift sequence, preserving part of their initial petroleum potential until the onset of Alpine flexuring and thrusting, play an important role on the Arabian platform (Silurian shales; Gilmour and Mäkel, this volume) and in Western and Central Europe (mainly Carboniferous and Autunian; Ziegler, 1990). Numerous Mesozoic source rocks have been identified within the Mesozoic syn-rift series (mainly Triassic and Early Jurassic) and in the passive margin sequences of the former Tethys (mainly Late Jurassic to late Early Cretaceous). These pre-orogenic sequences account for most of the oil and thermal gas potential of the Alpine orogen and its associated basins.

In addition, organic-rich series (TOC values up to 10%) have been identified in the Oligocene syn-flexural fill of the East-Alpine and Carpathian foredeep (Menilite series); these are coeval with the prolific Maykop source-rocks of the Black Sea, Crimea and the foredeeps of the Great Caucasus and Southern Caspian. Based on oil/source-rock correlations and the occurrence of the oleanane biomarker, even in subthrust Mesozoic reservoirs of the foreland, these Oligocene series are believed to be the most efficient source-rock in the Outer Carpathians and the adjacent East-European foreland, from Poland to Romania (Ulmishek and Klemme, 1990; Koltun, 1992; Ten Haven et al., 1993; Lafargue et al., 1994; Bessereau et al., this volume). Similar facies occur in the German and Austrian Molasse basin where they are the primary source of accumulated oils (Zimmer and Wessely, Roeder and Bachmann, this volume). Oligocene series display also good TOC values in the successor Pannonian basin where they have been sufficiently buried, under a relatively high geothermal gradient, to enter the oil window and account for significant hydrocarbon reserves in Hungary and former Yugoslavia. In addition, Oligocene shales have a good source-potential in the Cenozoic rift basins of Western Europe (Vially and Trémolières, Torné et al., this volume)

The thick Mio-Pliocene terrigenous fill of the Carpathian and Periadriatic foredeeps (Apennines, Albanides) have TOC values averaging 1%. Mostly immature, these Neogene series account for large reserves of bacterially-generated gas, but only for minor oil (Kotarba, 1992; Anelli et al., this volume).

Sedimentary Versus Tectonic Burial of Source-Rocks

For most Alpine foreland fold-and-thrust belt systems, available surface and sub-surface geological and geophysical data provide sufficient constraints to construct reliable regional structural cross-sections, extending from the autochthonous foreland to the frontal parts of the thrust belt. Combined with a good biostratigraphic dating of the syn-orogenic sequences, this permits construction of high quality balanced cross-sections and their step-wise palinspastic restoration, retracing the evolution of the respective area from the onset of deformation to its Present configuration (Bally et al., 1988; Roure et al., 1993; Zoetemeijer et al., 1993).

Forward kinematic modelling permits to retrace the maturation history of potential source-rocks within an evolving Alpine foredeep basins, i.e. during their initial sedimentary burial and their subsequent tectonic burial beneath the advancing allochthonous units. Ultimately, also uplift and erosion, related to tectonic accretion of individual units into the Alpine orogenic wedge, can be simulated. Coupled with palaeo-thermal reconstructions and transformation kinetics of kerogens into hydrocarbons, these new techniques provide an efficient tool to date the timing of source-rock maturation and to evaluate migration pathways between hydrocarbon kitchens and potential traps (Roure and Sassi, 1995).

Distinct source-rocks frequently coexist in a single Alpine foreland basin. However, due to lateral and vertical changes in their distribution, they usually contribute to independent petroleum systems, characterized by unique timing of maturation, hydrocarbon expulsion and migration. Therefore, it is essential to obtain an impression of potential migration pathways between source areas and traps and the timing of trap development, before drilling a prospect, in order to decrease exploration risks in such complex areas as the Alpine orogen.

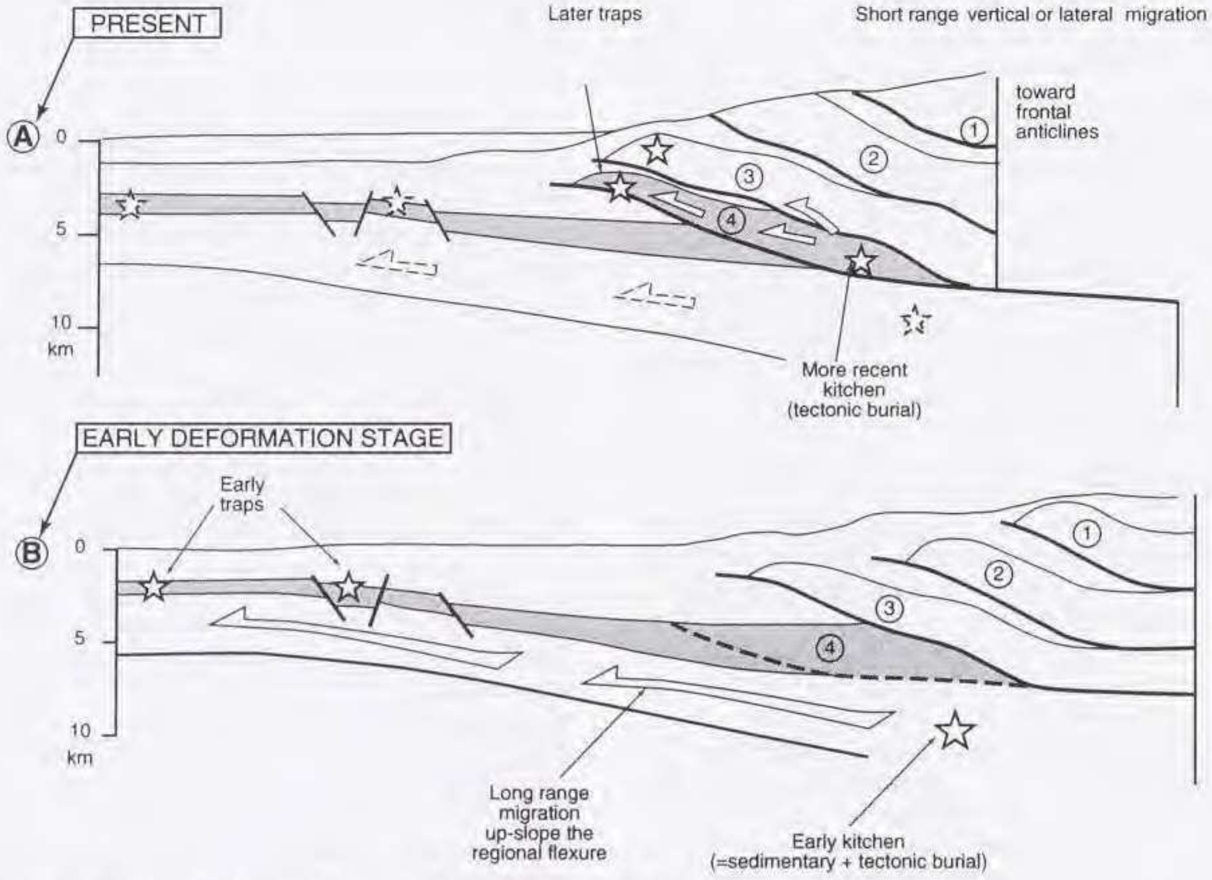

FIG. 8. Evolution of a foreland fold-and-thrust belt system and distribution of effective petroleum systems:
a) Sedimentary burial, early maturation and long-range migration pathways
b) Tectonic burial, late maturation and short range migration pathways.

Long-Distance Lateral Versus Short-Distance Vertical Migration

Calibration and reconstruction of palaeo-temperatures and -hydrodynamics (convective heat and fluid transfers) has hardly been addressed for the external imbricate structures of the different Alpine fold-and-thrust belts. However, distinct episodes of petroleum generation and migration are usually recognized in the Carpathians, Apennines and Albanides, which constitute the most productive petroleum provinces in the European part of the Alpine orogen (Roure and Howell, 1996).

Most frequently, oil is generated early in foreland basins, resulting in long range migration of the first hydrocarbon products from the foredeep source area toward the foreland, up-slope the regional flexure. This buoyancy driven mechanism is even facilitated by regional hydrodynamics, accounting for recharge of meteoric waters in the foothills and discharge in the foreland in the area of a potential forebulge, if present (Fig. 8). Thus, early long-distance updip migration of oils generated by Triassic source-rocks in the Albanian foredeep, charging the Aquila field, located on the eastern Puglia slope in the Adriatic (Anelli et al., this volume), is indicated. Apparently, the Mesozoic reservoirs at Lopushnia oil field in the Ukrainian sub-thrust foreland (Izotova and Popadyuk; Sovchik and Vul, this volume), were laterally charged by the Oligocene series of the Outer Carpathians; these are presently entirely detached from their former substratum and are now accreted to the allochthon (Lafargue et al., 1994).

A residual oil potential is eventually preserved within the allochthonous units or in the underthrusted foreland, accounting for late phases of maturation and migration. Under such conditions, expelled hydrocarbon can hardly reach the foreland as frontal antiform structures are already well developed and provide traps; instead, hydrocarbons generated during such late stages are preferentially trapped in nearby structures, requiring short distance lateral and/or vertical migration. This concept applies, for instance, for the deeply buried duplexes of the Borislaw-Pokut zone of the Ukrainian Outer Carpathians (Sovchik and Vul, this volume) and the subthrust para-autochthonous plays of the Southern Apennines (Casero et al., 1991; d'Andrea et al., 1993; Anelli et al, this volume).

On the other hand, hydrocarbons generated by source-rocks forming part of the under-thrusted sedimentary cover of the foreland may migrate vertically into the allochthon or into neo-autochthonous basins (Fig. 8). An example of such a "plumbing system" are the oil and gas accumulations in the Neogene fill of the Vienna Basin and in the underlying Austroalpine allochthon; these were charged hydrocarbons generated by autochthonous Late Jurassic basinal shales (Ladwein et al., 1991, Zimmer and Wessely, this volume). Similarly, the structures of the East-Taurus foothills thrust belt were charged by Silurian source-rocks of the autochthonous foreland sedimentary cover (Gilmour and Mäkel, this volume).

CONCLUSIONS

Opening of the different constituent oceanic basins of the Mesozoic Tethys was controlled by a sequence of rifting cycles, the kinematics of which changed with the progressive development of discrete plate boundaries first between Gondwana and Laurasia and later between Eurasia and Laurentia-Greenland. During these opening phases of Tethys and the Atlantic, a sinistral translation between Africa-Arabia and Europe and the interaction with intervening microcontinents, such as the Italo-Dinarides block, is held responsible for the development of first subduction zones and the onset of the Alpine orogenic cycle. With the Senonian onset of convergence of Africa-Arabia and Europe, new subduction zones developed and progressive closure of the different Tethys oceanic basins was followed by multiple and diachronous collisional events. However, the preservation of remnant Tethys oceanic basins in the Ionian Sea and the Eastern Mediterranean shows, that continent-to-continent collision has not yet occurred along the entire Alpine-Mediterranean suture of Africa-Arabia and Europe. Moreover, Neogene continental rifting, lateral block escape and subduction slab roll back has governed the opening of the oceanic Algero-Provençal and the partly oceanic Tyrrhenian basins.

The different fold-and-thrust belts of the Alpine orogenic system display highly variable architectures. These are partly controlled by the intensity of collisional coupling between the respective orogenic wedge and its cratonic foreland (and hinterland), and partly by the availability of a thick passive margin sedimentary wedge, or its absence. Imbricated passive margin wedges characterize, for instance, the external elements of the Apennines, the Dinarides-Albanides and the East-Taurides. In contrast, major nappes, derived from the southern margin of the South Penninic Ocean, directly override the undeformed foreland of the Eastern Alps which extends some 100 km beneath these nappes. In the Central and Western Alps, increasing collisional coupling between the foreland and the evolving orogenic wedge resulted in imbrication of the foreland crust, uplift of external crystalline massifs and deformation of the overlaying stack of nappes. In contrast, the Flysch Carpathians consist of an accretionary wedge which was thrusted over the essentially undeformed autochthonous foreland.

Most of the Alpine fold-and-thrust belts are associated with more or less pronounced flexural foreland basins; however, in some cases these were destroyed by late thrust propagation into the foreland. The Alpine foreland basins display major variations in their their architecture and the facies development of their sedimentary fill. An array of minor syn-flexural normal faults characterizes the

German and Austrian Molasse Basin (Roeder and Bachmann, Zimmer and Wessely, this volume). In contrast, the Carpathian foreland basins are characterized by a limited number of major syn-flexural faults. On the other hand, thrust propagation into the foreland plays an important role in the Apennine foredeep (Anelli et al., this volume). Whereas the Swiss Molasse Basin is characterized by shallow marine and continental clastics, lacking effective reservoir/seal pairs (Ziegler et al, this volume), the Molasse Basin of Austria contains Oligocene and early Miocene deeper water clastics and shales, grading upwards into deltaic series, which provide for several reservoir-seal pairs (Zimmer and Wessely, this volume). Similarly, the flysch-type sediments of the Apennine foreland basins, which grade up into a Pleistocene deltaic complexes, contain multiple effective reservoir/seal pairs. In contrast, the sedimentary fill of the East-Taurus foreland basin consists of marls, evaporites and carbonates (Gilmour and Mäkel, this volume).

Compressional intra-plate deformations characterize both the European and the Africa-Arabia platform. These developed in response to collisional coupling of these forelands with the Alpine orogen. Early collisional foreland deformations occur in the Carpathian and East-Alpine forelands, where they caused partial destruction of the passive margin sedimentary prism and inversion Mesozoic tensional basins and the upthrusting of basement blocks as far north as Denmark and southern Sweden. Late collisional foreland deformations occur, for instance, in the forelands of the Western and Central Alps and the Pyrenees. Examples of thin-skinned foreland fold-an-thrust belts are the Lombardian belt of the Southern Alps (Ziegler et al., this volume), the Jura Mountains of Switzerland and France (Philippe et al, this volume) and the Prerifain chains of Morocco (Zizi, this volume). Their development caused partial destruction of pre-existing syn-orogenic flexural basins. Basement involving up-thrusted blocks characterize the Bohemian Massif in the foreland of the Eastern Alps (Ziegler, 1990). Inversion of major Mesozoic grabens in Europe, in Iberia and on the African-Arabian Platform probably involved the entire crust and possible also the mantle lithosphere (Ziegler et al., 1995).

Eocene and later development of the Rhine-Rhône-Valencia and East Africa-Red Sea-Libyan-Pelagian Shelf rift systems caused disruption of the sedimentary cover of the European and Africa-Arabian platforms, particularly across major thermal domes. This had repercussions on the hydrodynamic conditions in remnant platform basins and their hydrocarbon habitat.

The petroleum systems of the external parts of the Alpine orogen, its foreland and internal basins are highly variable. They can rely either on pre-rift, syn-rift or syn-flexural source-rocks or a combination thereof. Some of these source-rocks attained maturity already during the passive margin or flexural basin stage; others reached maturity only during the emplacement of allochthonous units. Each basin has its own case history.

The petroleum exploration history of the Alpine orogen and its associated basins commenced in the early Nineteenth century. First hydrocarbon exploration efforts were based on surface seeps, concentrated in the shallow, frontal anticlines of the Outer Carpathians of the Ukraine and Romania. In the course of time, improved geophysical methods provided new tools for imaging sub-surface structures. This resulted in new discoveries of oil and biogenic gas in such foreland basins as the Po Plain, the Adria, the German and Austrian Molasse Basin and in the Aquitaine Basin, as well as in the Pannonian and Vienna neo-autochthonous basins. With the development of static corrections and the development of CDP-methods, and ultimately of 3D-seismic, imaging of even structurally complex areas has become possible, thus providing access to complex thrusted structures (Le Vot et al., this volume) and subthrust prospects of the Lopushnia (Carpathians) and Tempa Rossa type (Southern Apennines; Roure and Sassi, 1995; Anelli et al., this volume).

No doubt, future exploration efforts in the external parts of the Alpine orogen an beneath the Neogene fill of the Pannonian Basin will yield further oil and thermal gas discoveries, provided it can be established that efficient petroleum systems are available, have survived the most recent deformations and that only minor hydrocarbon re-migration has occurred.

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